INTERNATIONAL MAX PLANCK RESEARCH SCHOOL

PT FS FOR PRECISION TESTS OF FUNDAMENTAL SYMMETRIES

Electroweak and Conformal Symmetry Breaking by a Strongly Coupled (Hidden) Sector

Kher Sham Lim
Max-Planck-Institut für Kernphysik

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Paris
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Based on hep-ph/1310.4423, JHEP 1312 (2013) 076 by M. Holthausen, J. Kubo, KSL and M. Lindner
hep-ph/1403.4262 by J.Kubo, KSL and M.Lindner
hep-ph/1405.1052 by J.Kubo, KSL, M.Lindner

This talk is not about Technicolor or Composite Higgs!

We know Higgs boson exist!

The Nobel Prize in Physics 2013
François Englert, Peter Higgs

The Nobel Prize in Physics 2013

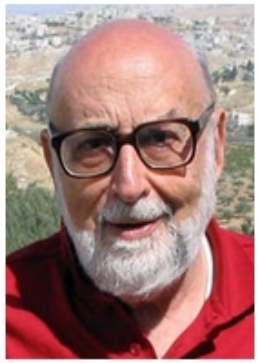


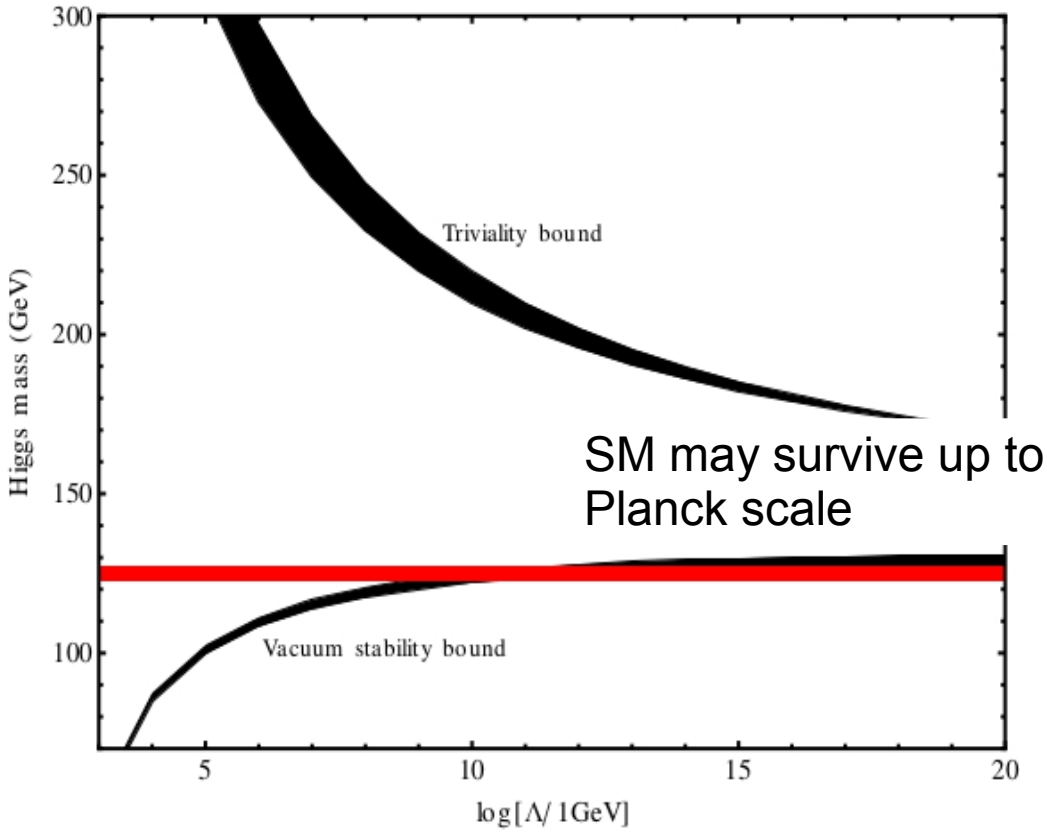
Photo: Pnicolet via Wikimedia Commons

François Englert

Photo: G-M Greuel via Wikimedia Commons

Peter W. Higgs

The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs ***"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"***



SM may survive up to Planck scale

Holthausen, Lim, Lindner '12
Degrassi et al. '12
Buttazzo et al. '13
Bezrukov et al. '12

BSM?

Dark energy

Strong CP problem

THE HIERARCHY PROBLEM

Inflation

Dark matter

Neutrino mass

Baryogenesis

Supersymmetry?

$$\delta m_h^2 \propto f(\lambda, g_i ...)\Lambda^2$$

Compositeness?

Extra Dimension?

BSM? Dark energy Strong CP problem

THE HIERARCHY PROBLEM

Inflation Dark matter Neutrino mass Baryogenesis

But where are the new physics? ?

$$\delta m_h^2 \propto f(\lambda, g_i ...)\Lambda^2$$

Solutions getting pushed into special corner!

Long-held belief on naturalness must be critically reexamined!

Introducing Conformal Symmetry

$$\delta m_h^2 \propto f(\lambda, g_i ...)\Lambda^2 + m_{\rm new}^2 \log\left(\frac{\Lambda}{m_{\rm new}}\right)$$

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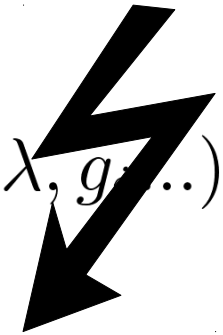
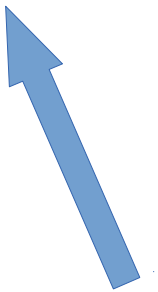


This term violates Conformal Symmetry



Might create a large hierarchy if new physics is still in the framework of QFT. But Wilsonian picture might not apply to Planck scale physics!

Introducing Conformal Symmetry

Avoid large hierarchy $=$ Add new CS sector at TeV scale and let the theory flow to Planck scale

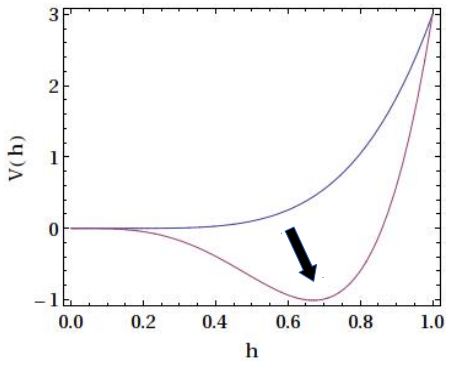
$$\delta m_h^2 \propto f(\lambda, g, ...)\Lambda^2 + m_{\rm new}^2 \log\left(\frac{\Lambda}{m_{\rm new}}\right)$$

This term violates Conformal Symmetry

Might create a large hierarchy if new physics is still in the framework of QFT. But Wilsonian picture might not apply to Planck scale physics!

Introducing Conformal Symmetry

Through RG evolution, the scalar potential develop flat direction, quantum correction shift the vev to non-vanishing value: Coleman-Weinberg



Start with *classical* scale invariant lagrangian

$$\mathcal{L}_{\rm SM} \to \mathcal{L}_{{\rm SM},m^2\to 0}$$

EW scale is radiatively generated

Crucial: $\lambda_{hs} H^\dagger H S^\dagger S$

(Additional) gauge interaction grows strong and dynamically sets a condensation scale

$$\langle \bar{\phi}\phi \rangle \sim \Lambda^3 \Rightarrow \lambda_{hs}\Lambda^2 H^\dagger H$$

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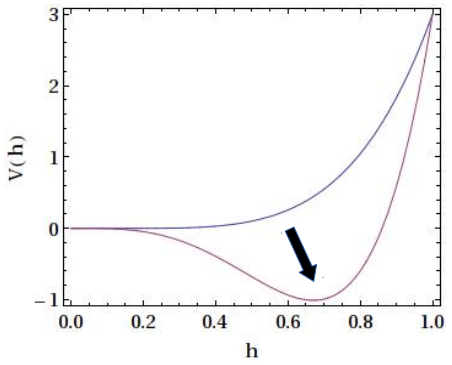

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Focus Today

Introducing Conformal Symmetry

Very active field of research!

Bardeen '95
Fatelo, Gerard, Hambye, Weyers '95
Hempfling '96
Hambye '96
Meissner, Nicolai '07
Foot, Kobakhidze, Volkas '07
Foot, Kobakhidze, McDonald, Volkas '07
Chang, Ng, Wu '07
Hambye, Tytgat '08
Iso, Okada, Orikasa '09
Holthausen, Lindner, Schmidt '10
Hur, Jung, Ko, Lee '11
Hur, Ko '11
Ishiwata '12
Lee, Pilaftsis '12
Khoze '13
Kawamura '13
Gretsch, Monin '13
Carone, Ramos '13
Khoze, Ro '13
Englert, Jaekel, Khoze, Spannowsky '13
Farzinnia, He, Ren '13
Abel, Mariotti '13
Heikinheimo, Racioppi, Raidal, Spethmann, Tuominen '13
Steele, Wang, Contreras, Mann '13
Hambye, Strumia '13
Holthausen, Kubo, Lim, Lindner '13
Hashimoto, Iso, Orikasa '14
Hill '14
Guo, Kang '14
Radovcic, Benic '14
Khoze, McCabe, Ro '14
Kubo, Lim, Lindner '14
Allison, Hill, Ross '14
Farzinnia, Ren '14
Davoudiasl, Lewis '14

I am sorry if I left out your paper

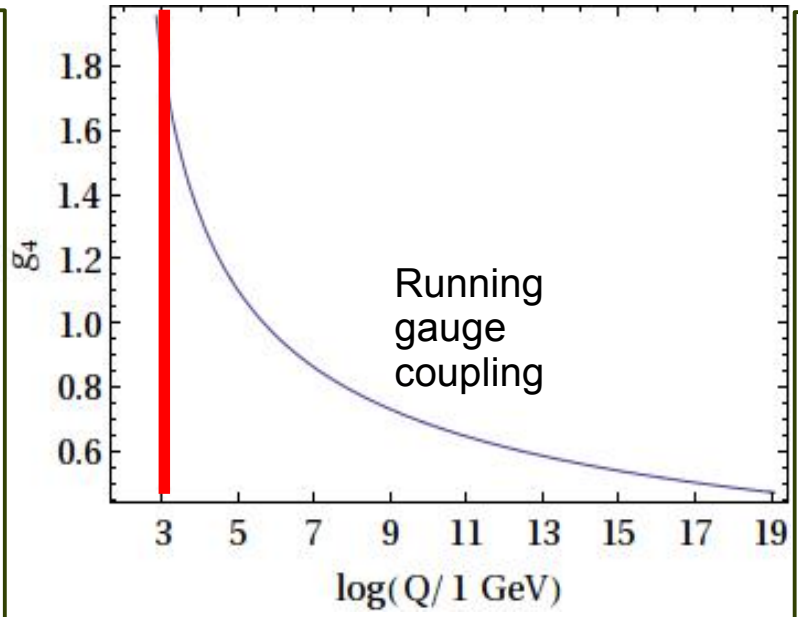
Generating Electroweak Scale

- Strong hierarchy between EW and Planck scale.
- QCD scale can be explained by running couplings and dimensional transmutation.
- Would be nice if EW sector can mimic such mechanism.

Direct Transmission

$$\lambda_{hs} H^\dagger H \langle S^\dagger S \rangle$$

$$\lambda_{hs} \Lambda^2 H^\dagger H$$



$$\lambda_{hs} H^\dagger H S^\dagger S$$

Indirect Transmission

$$\langle \bar{\psi}\psi \rangle \sim \Lambda^3$$

$$y S \langle \bar{\psi}\psi \rangle$$ shift the S field, S obtains a vev

$$\lambda_{hs} v_s^2 H^\dagger H$$

Generating Electroweak Scale

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Part 1

Direct Transmission

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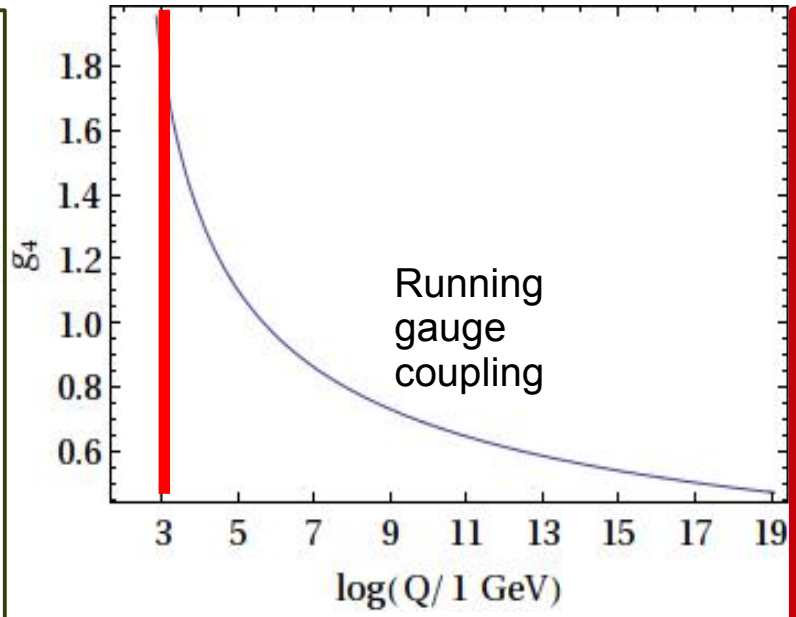

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Indirect Transmission = Conformal + Strong hidden sector

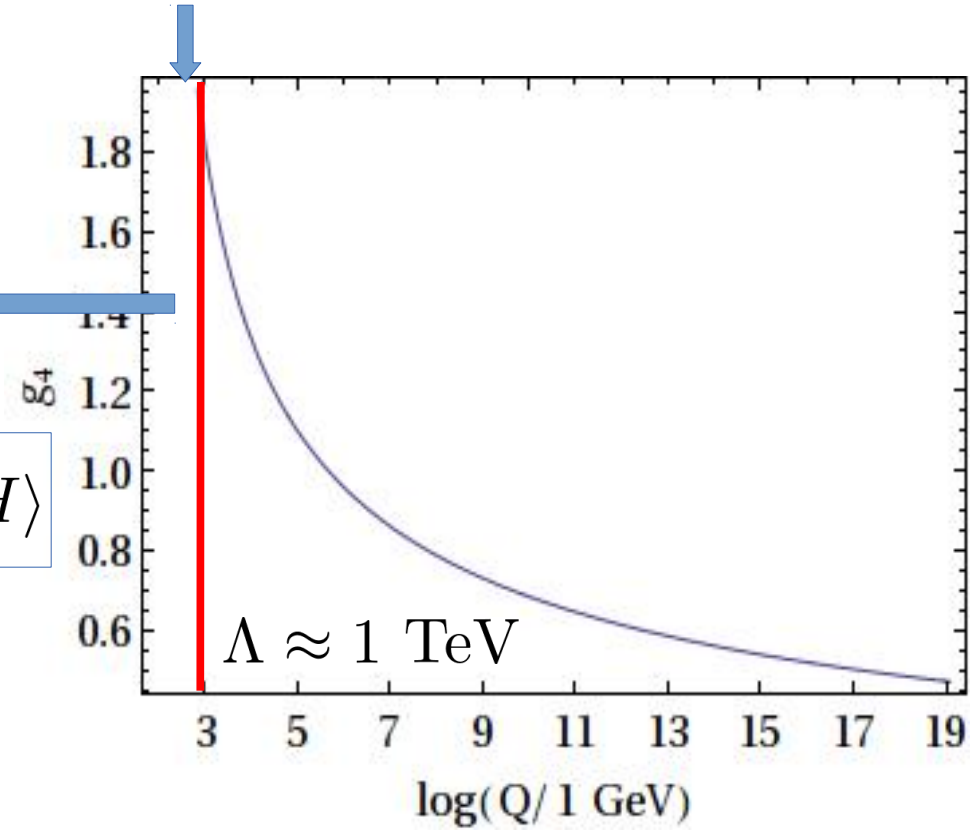
$\langle \bar{\psi}\psi \rangle$

Dynamical chiral symmetry breaking of hidden fermions

Bonus: Dark pions as dark matter candidate $\langle \bar{\psi}\gamma_5\psi \rangle$

The condensation scale is transferred to SM by Higgs portal.

$\langle \bar{\psi}\psi \rangle \to \langle S \rangle \to \langle H \rangle$



Strongly coupled hidden sector runs ala QCD

Holthausen, Kubo, Lim, Lindner '13
Hur, Jung, Ko, Lee '11
Hur, Ko '11
Heikinheimo, Racioppi, Raidal, Spethmann, Tuominen '13

Concrete Model

$\mathrm{SU}(3)_H$

$\mathrm{fundamental}, \mathrm{SU}(3)_L \times \mathrm{SU}(3)_R$

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}+S} - \frac{1}{2}\mathrm{Tr}\ F^2 + \mathrm{Tr}\ \bar{\psi}(i\gamma^\mu D_\mu - yS)\psi$$

Singlet mediator

$$V_{\mathrm{SM}+S} = \lambda_H (H^\dagger H)^2 + \frac{1}{4}\lambda_S S^4 - \frac{1}{2}\lambda_{HS} S^2 (H^\dagger H)$$

NJL approach

$\Phi_{ij} = \bar{\psi}_i (1 - \gamma_5)\psi_j$

$$\mathcal{L}_{\mathrm{NJL}} = \mathrm{Tr}\ \bar{\psi}(i\gamma^\mu \partial_\mu - yS)\psi + 2G\ \mathrm{Tr}\ \Phi^\dagger \Phi + G_D\ (\det \Phi + h.c.)$$

- Advantage of having 3 dark color and 3 flavors = Can use QCD data to scale up spectrum
- Nambu-Jona-Lasinio approach allows us to determine a lot of paramaters dynamically.
- Less free parameters if we mimic QCD, but in general can be of any gauge group and flavor.

After all the tedious algebras...

$\langle\bar{\psi}\psi\rangle$ CP even scalar, mixes with *h* and *S*

$$\mathcal{L}_{\rm NJL} \supset i\ {\rm Tr}\bar{\psi}\gamma^\mu\partial_\mu\psi - \left(\sigma + yS - \frac{G_D}{8G^2}\sigma^2\right){\rm Tr}\bar{\psi}\psi - i{\rm Tr}\bar{\psi}\gamma_5\phi\psi - \frac{1}{8G}\left(3\sigma^2 + 2\sum_{a=1}^{8}\phi_a\phi_a\right)$$
$$+\frac{G_D}{8G^2}\left(-{\rm Tr}\bar{\psi}\phi^2\psi + \sum_{a=1}^{8}\phi_a\phi_a{\rm Tr}\bar{\psi}\psi + i\sigma{\rm Tr}\bar{\psi}\gamma_5\phi\psi + \frac{\sigma^3}{2G} + \frac{\sigma}{2G}\sum_{a=1}^{8}(\phi_a)^2\right)$$

$\sim \langle\bar{\psi}\gamma_5\psi\rangle$

Dark pions

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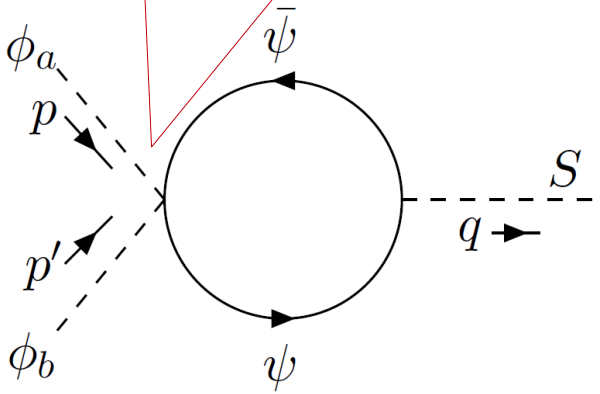

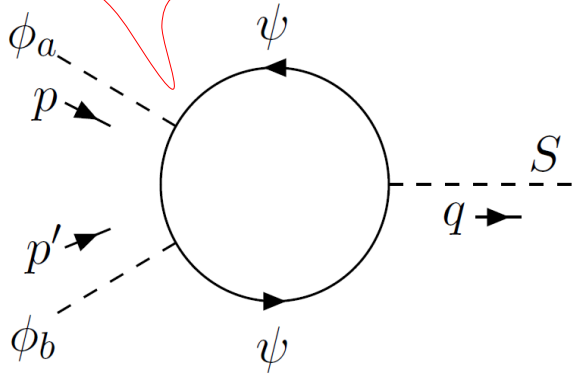

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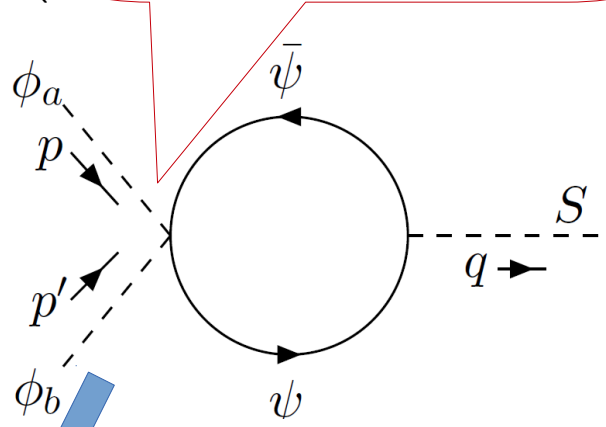
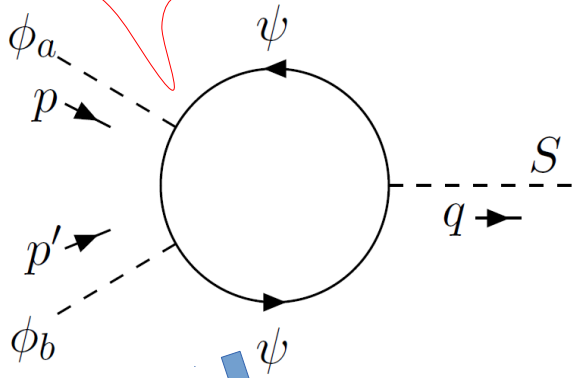
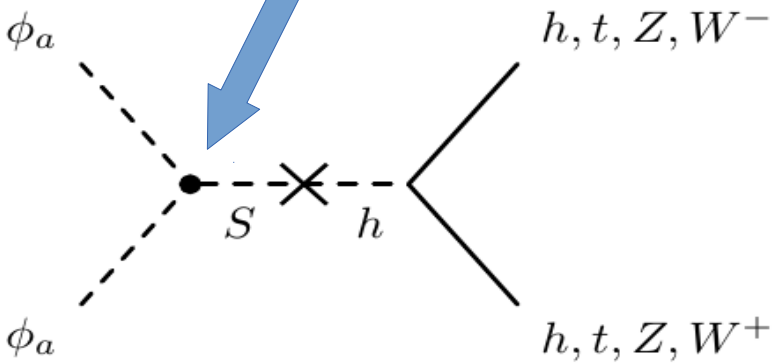
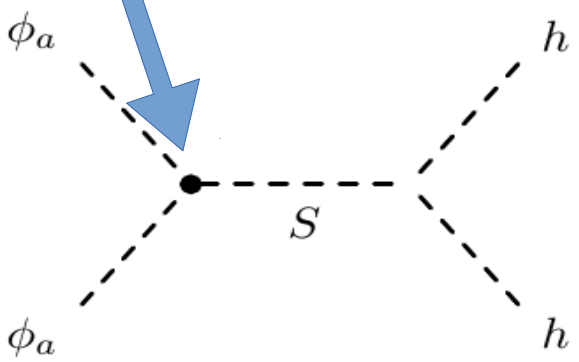
Dark pions

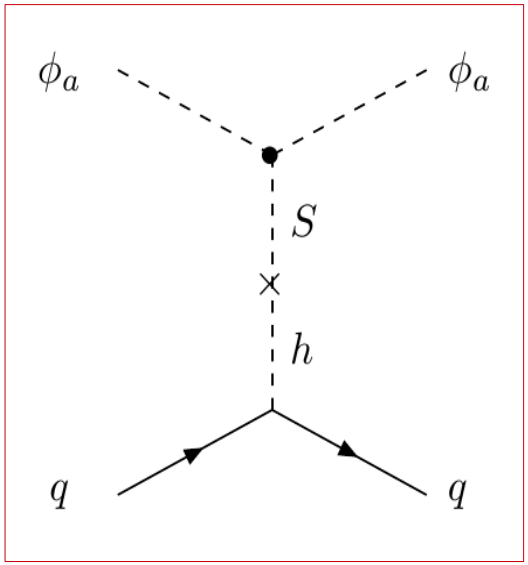


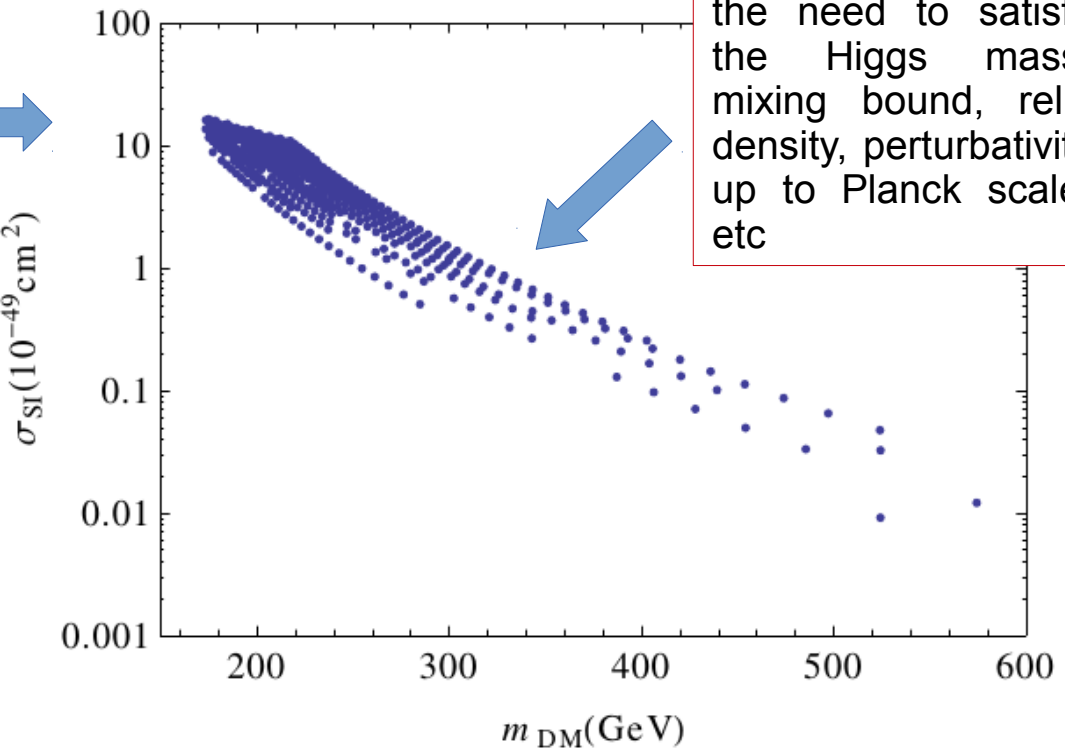






Direct Detection Prospect



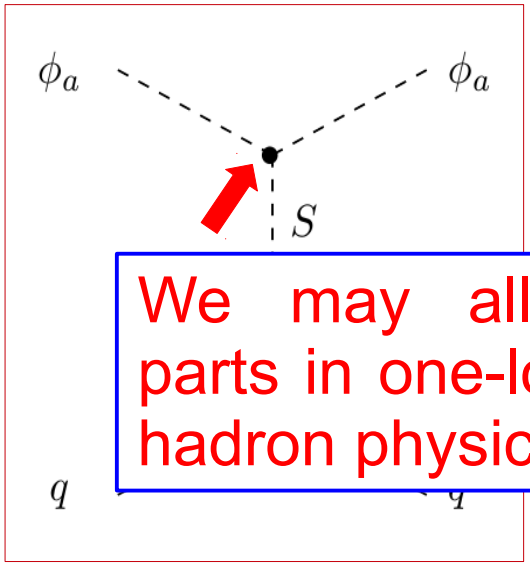


Caused by restrictive parameter space and the need to satisfy the Higgs mass, mixing bound, relic density, perturbativity up to Planck scale, etc

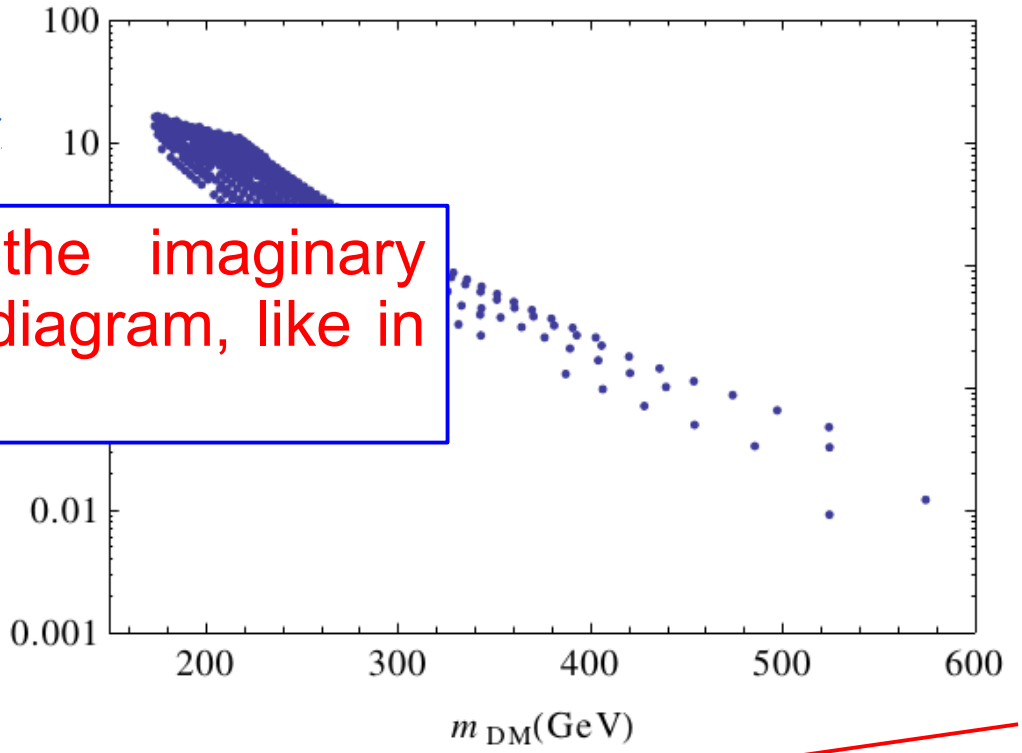
Naively

The model predicts no signal in LUX and XENON1T. But the small range of parameter space can be confirmed or excluded by next generation DM direct detection.

Direct Detection Prospect



We may allow the imaginary parts in one-loop diagram, like in hadron physics.



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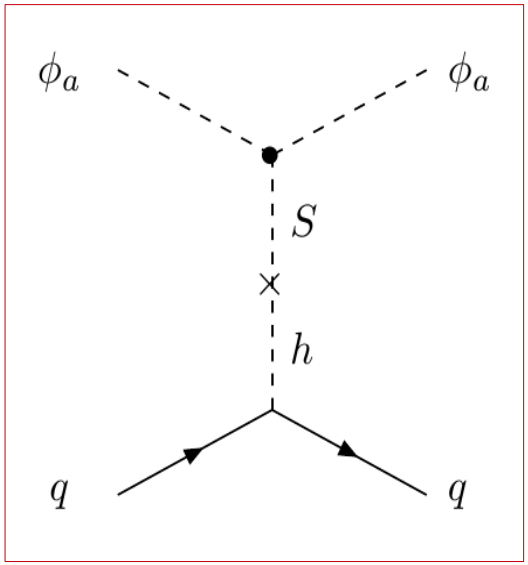
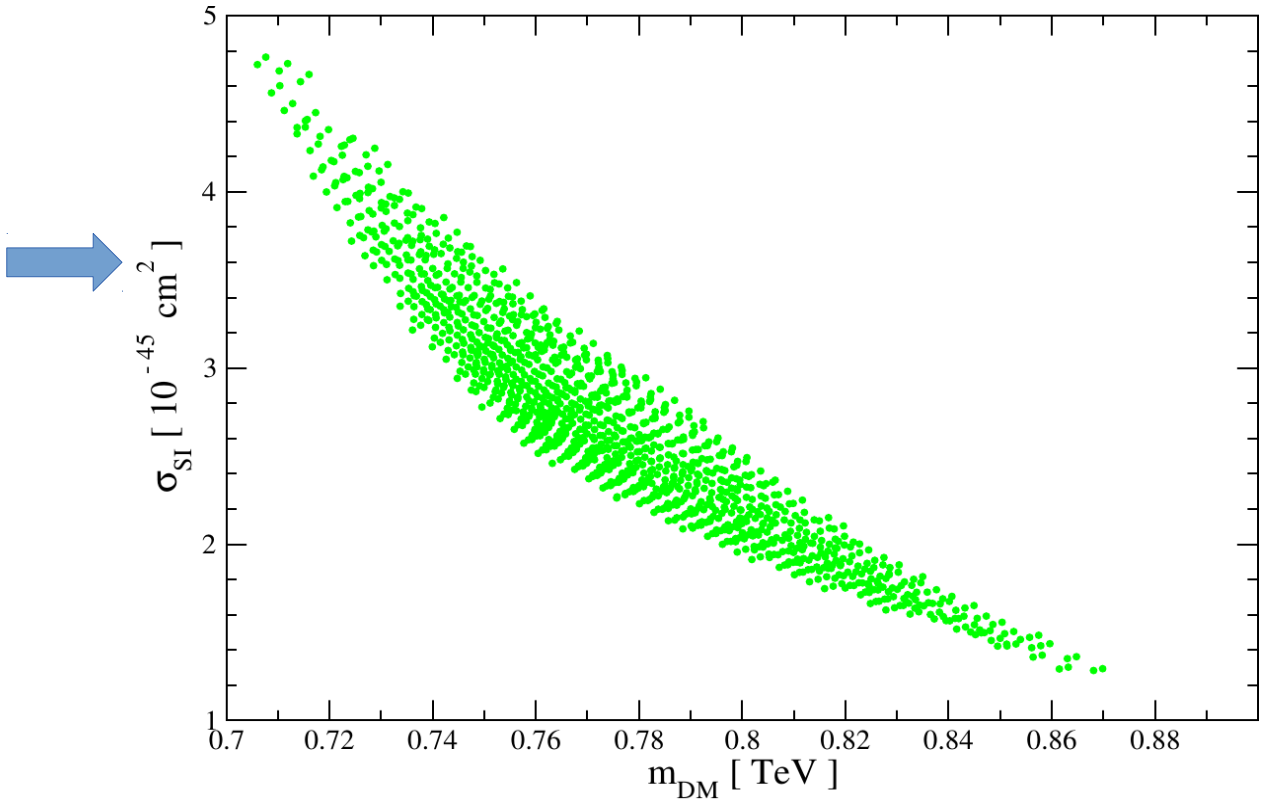


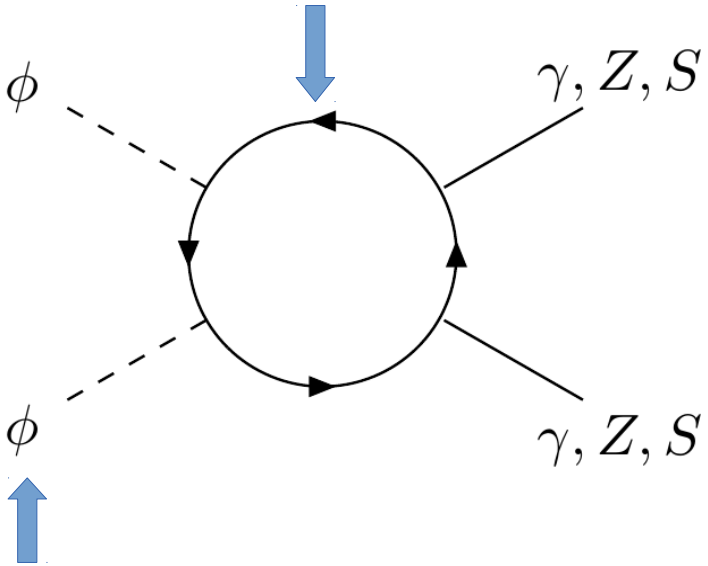


Limited Parameter Space can be probed by XENON1T!

There is still an U(1)

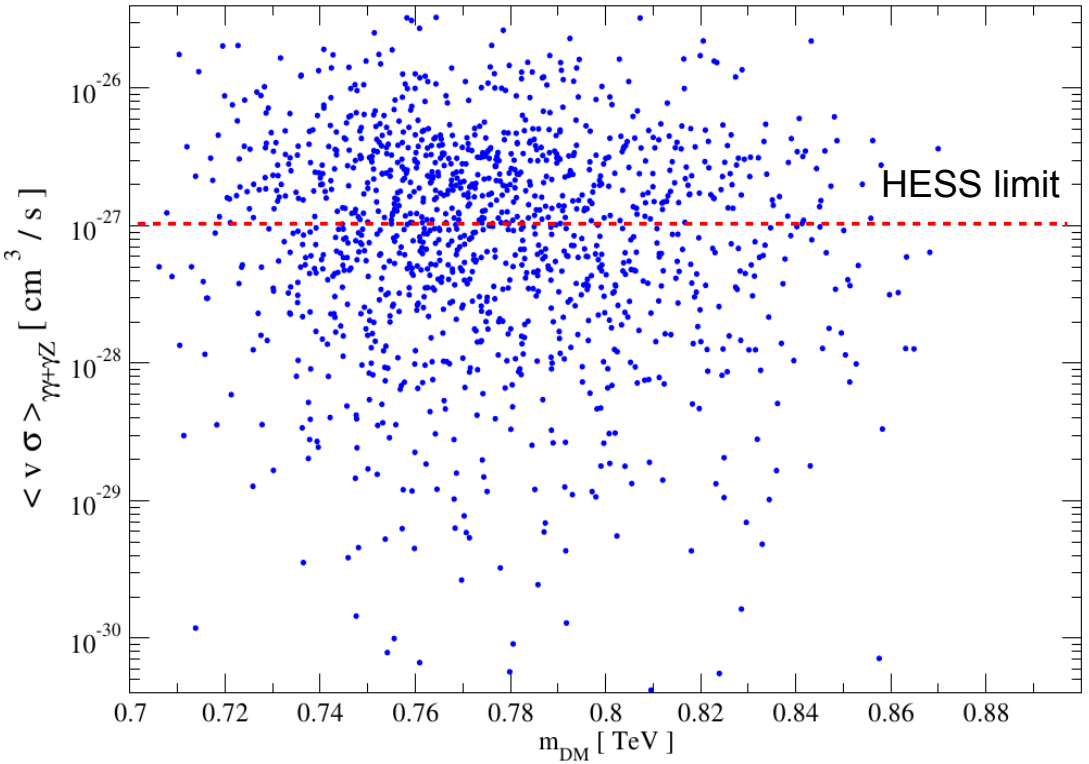
We can exploit this free lunch by identifying it with electromagnetism

Charged dark fermion



DM remains neutral

e.g. Q = 1/3



Highly non-trivial to use NJL approach while maintaining gauge invariance. Needs “least subtraction method” (More fun stuffs in our paper).

End of Part 1

Generating Electroweak Scale

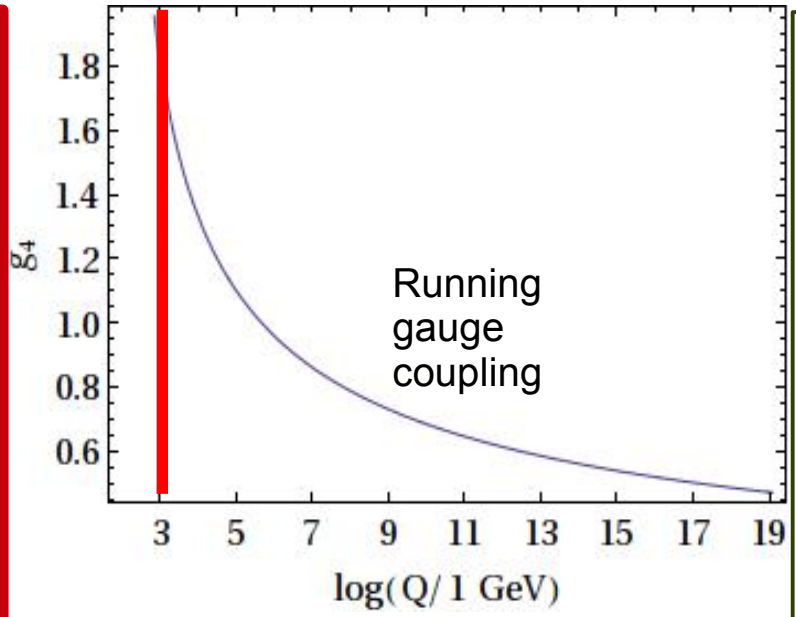
- Strong hierarchy between EW and Planck scale.
- QCD scale can be explained by running couplings and dimensional transmutation.
- Would be nice if EW sector can mimic such mechanism.

Part 2

Direct Transmission

$$\lambda_{hs} H^\dagger H \langle S^\dagger S \rangle$$

$$\lambda_{hs} \Lambda^2 H^\dagger H$$



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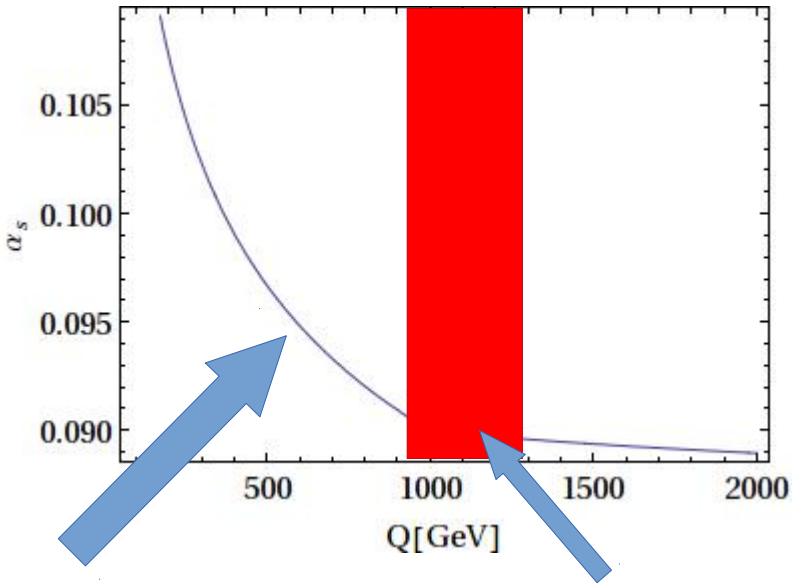
Direct Transmission = Scalar Bound State

For instance: QCD



- But strong coupling is weak at TeV?
- Possible if the representation of this new field is large

$$C_2(S)\alpha_s(\Lambda) \gtrsim 1$$

(compensate)

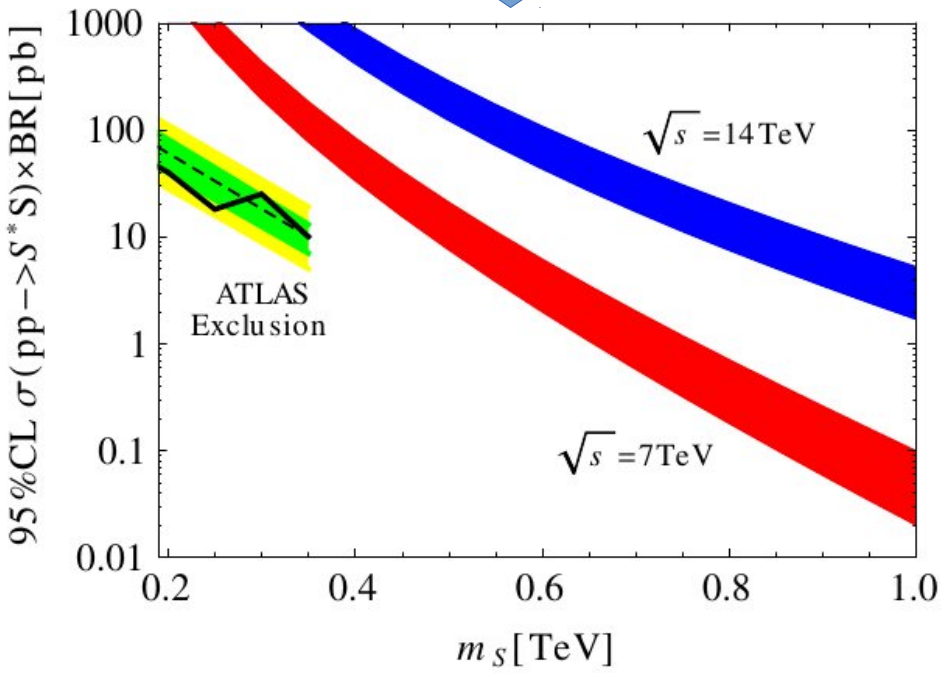
Low energy
QCD unaltered

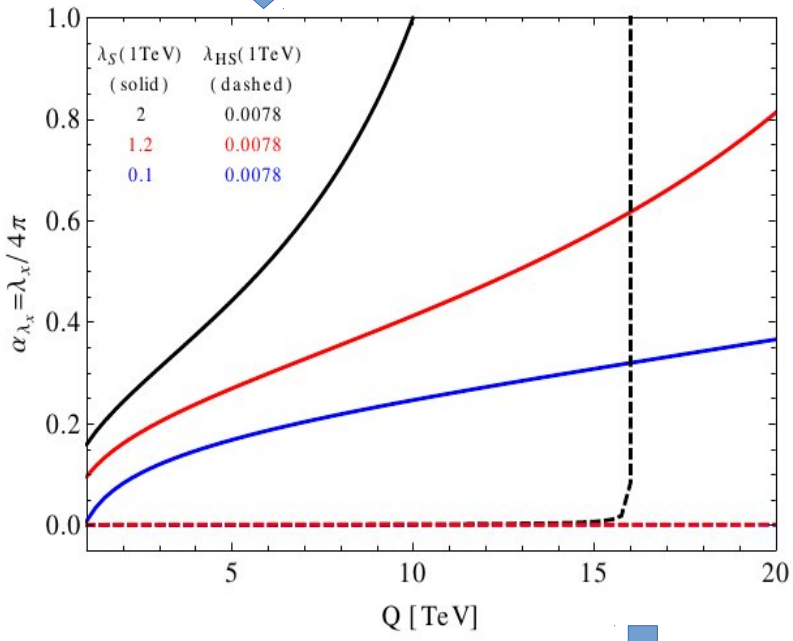
Extra condensate at TeV?

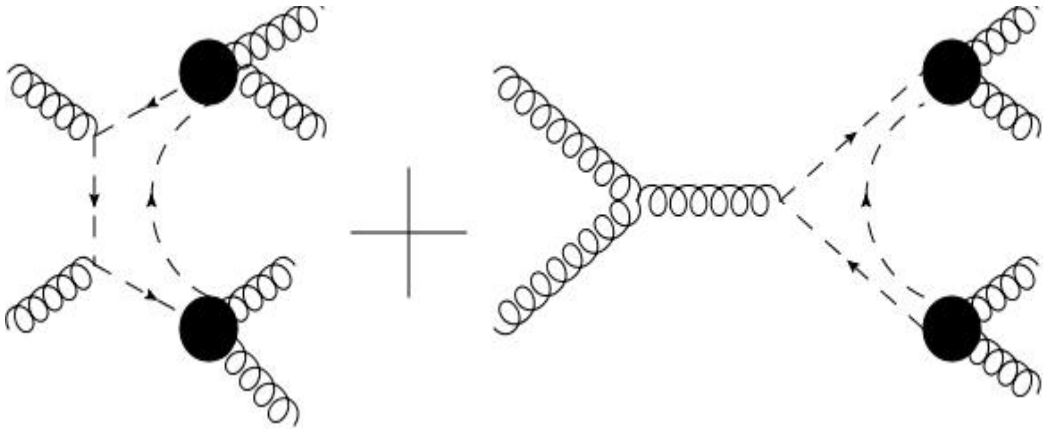
$$\lambda_{hs} H^\dagger H S^\dagger S \to \lambda_{hs} H^\dagger H \langle S^\dagger S \rangle = \lambda_{hs} \Lambda^2 H^\dagger H$$

Rep $(\boldsymbol{R})$	$C_2(\boldsymbol{R})$	$C(\boldsymbol{R})$	Λ (GeV)
8	3	3	1
10	6	15/2	20
15	16/3	10	10
15′	28/3	35/2	1000
21	40/3	35	10^5

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM},m^2\to 0} + (D_{\mu,ij}S_j)^\dagger (D^\mu_{ik}S_k) + \lambda_{HS} H^\dagger H S^\dagger S - \lambda_{\mathbf{1}_i}\left[\bar{\boldsymbol{S}}\times\boldsymbol{S}\times\bar{\boldsymbol{S}}\times\boldsymbol{S}\right]_{\mathbf{1}_i}$$







$$350\,\mathrm{GeV} \lesssim m_S \lesssim 3\,\mathrm{TeV}$$

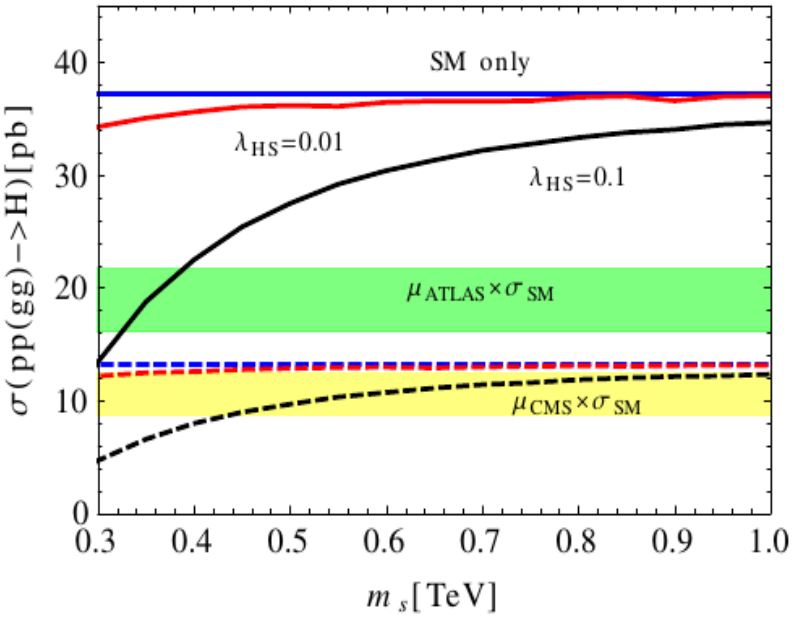
Can be detected or ruled out by the LHC!

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM},m^2\to 0} + (D_{\mu,ij}S_j)^\dagger (D^\mu_{ik}S_k) + \lambda_{HS} H^\dagger H S^\dagger S - \lambda_{\mathbf{1}_i}\left[\bar{\boldsymbol{S}}\times\boldsymbol{S}\times\bar{\boldsymbol{S}}\times\boldsymbol{S}\right]_{\mathbf{1}_i}$$

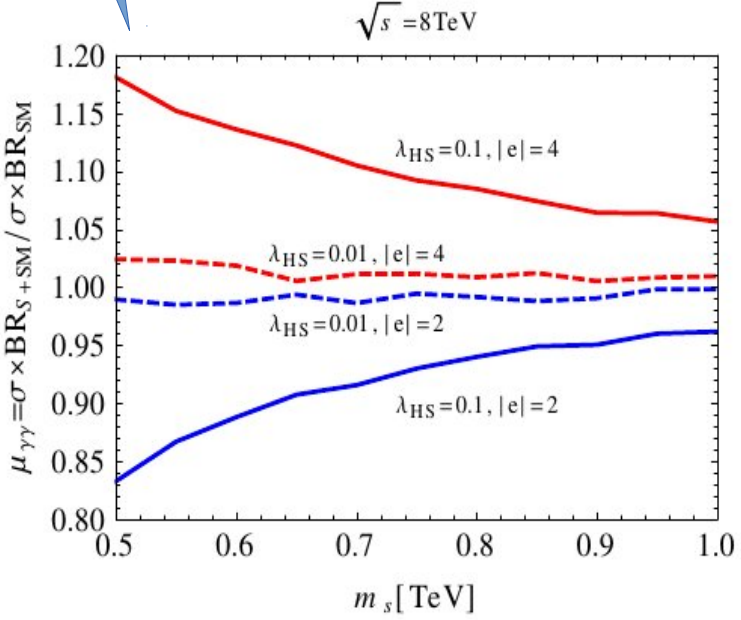
Suppression due to minus sign

Accidental U(1) symmetry in Lagrangian

$H \to \gamma\gamma$ enhanced for large electric charge



Higgs production rate in gluon fusion channel is reduced.



Summary

- With no sign of new physics from LHC, long-held belief on naturalness should be scrutnized.
- Conformal symmetry might act as protective symmetry as alternative solution to hierarchy problem.
- We propose 2 models that generate EW scale radiatively.

- A strongly coupled hidden sector model based on NJL where the spontaneous chiral symmetry breaking induces EWSB via singlet mediator.
- The strongly coupled hidden sector is a scaled up QCD → Less free parameter.
- The model provides natural DM candidates, i.e. the dark pions, which are stable under flavor symmetry.

- A QCD extension with scalar of larger irreducible representation that condenses at TeV scale, generating EW scale via dimensional transmutation.
- The mass of the extra scalar is very restrictive, and can be confirmed or ruled out by LHC.
- Higgs production rate in gluon fusion is $H \to \gamma\gamma$ enhanced. Accidental U(1) symmetry may enhance

A new way of model building?

Thank you :-)